



King's Research Portal

DOI:

[10.1007/s11191-019-00079-5](https://doi.org/10.1007/s11191-019-00079-5)

Document Version

Publisher's PDF, also known as Version of record

[Link to publication record in King's Research Portal](#)

Citation for published version (APA):

Brock, R., & Hay, D. (2019). Keeping students out of Mary's (class)room. Approaches to supporting students' acquisition of non-propositional knowledge in science education. *Science and Education*, 28(9-10), 985-1000. <https://doi.org/10.1007/s11191-019-00079-5>

Citing this paper

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

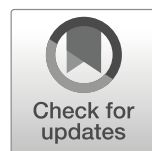
General rights

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Research Portal

Take down policy

If you believe that this document breaches copyright please contact librarypure@kcl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Keeping Students Out of Mary's (Class)room

Approaches to Supporting Students' Acquisition of Non-propositional Knowledge in Science Education

Richard Brock¹  · David Hay¹

Published online: 04 November 2019

© The Author(s) 2019

Abstract

Whilst many science educators, it is reported, associate knowledge with justified true belief (JTB), epistemologists have observed that the JTB model is an incomplete account of knowledge. Moreover, researchers from several fields have argued that developing scientific expertise involves not only the acquisition of knowledge that can be expressed in the form of a sentence, propositional knowledge, but also knowledge that cannot be articulated. This article examines the Mary's room thought experiment proposed by Frank Jackson and applies it to the context of science education. The thought experiment imagines a scientist, Mary, who has learned all the available scientific information about the physical properties of a tomato and the process of colour vision without directly experiencing the fruit. Jackson poses the question of whether Mary will gain new knowledge when she encounters a tomato for the first time. An argument is put forward that propositional and non-propositional knowledge are distinct, and a case is made for the value of non-propositional knowledge in learning science. An analogy is drawn between the scientist in Jackson's thought experiment and a learner in a science classroom who is taught propositional knowledge about a scientific concept without directly experiencing relevant phenomena. It is argued that this approach to teaching fails to develop the learner's non-propositional knowledge. A number of strategies for supporting learners to develop non-propositional knowledge are discussed. It is argued that science educators should consider the phenomenological curriculum, the experiences that students should be introduced to alongside propositional knowledge, in order to develop scientific understanding.

Keywords Learning · Knowledge · Epistemology · Practical work

✉ Richard Brock
richard.brock@kcl.ac.uk

¹ School of Education, Communication and Society, King's College London, Waterloo Bridge Wing, Franklin-Wilkins Building, Waterloo Road, London SE1 9NH, UK

1 The Goals of Science Education

Science education has been imagined to have a number of goals including the following: the acquisition of scientific knowledge and fostering understanding (Smith and Siegel 2016), the development of an ability to engage with communities of scientific practice (Aikenhead 1996), the appreciation of the nature of science (Osborne and Dillon 2008), the development of students' scientific reasoning (Kind and Osborne 2017), engagement in social action (Hodson 2010) and supporting students' aesthetic appreciation (Girod et al. 2003). Whilst achieving these varied aims, it is widely accepted that science education should support students to acquire knowledge of scientific concepts (Hodson 1985; Smith and Siegel 2004, 2016). However, the target knowledge of science education is often narrowly defined. It is reported that 'many science educators' (Sinatra et al. 2003, p. 511) have accepted a model of knowledge as justified true belief; that is, a person is said to know something if they hold a proposition that (a) is true, (b) they believe is the case and (c) they have good reason for believing (Klein 1971).

Whilst the justified true belief model of knowledge is widely discussed, it has been critiqued by the proposal of cases in which justified true beliefs are intuited to fall short of the status of knowledge and justified true belief's apparent incompleteness as a representation of knowledge has led to its rejection by many epistemologists (Gettier 1963; Turri 2012). A consensus model of knowledge that overcomes the limitations of the justified true belief definition is yet to emerge (Bigelow 2006; Hetherington 2011). The justified true belief model suggests that knowledge is propositional (Moser 1987); that is, knowledge of a fact is expressed in the clause of a sentence following the word 'that' (Carter and Poston 2018), for example, 'I know that whales are mammals'. Whilst several accounts of knowledge have been proposed as alternatives to the justified true belief model, they mostly retain a propositional form. Such definitions are problematic as propositional knowledge alone does not fully describe the epistemic states a learner can possess (Henderson and Horgan 2000; Shapiro and Stolz 2019; Weisberg and Newcombe 2017) and non-propositional knowledge is seen as a significant aspect of scientific knowing (Collins 2010; diSessa 1993).

Despite arguing that the separation should be discarded, Stanley and Williamson (2001) reported that a distinction between propositional knowledge and other forms of knowing is widely accepted by philosophers. A variety of models of non-propositional knowledge have been proposed, including the following: *technê* (Aristotle 2014), knowledge-how (Ryle 1945), tacit knowledge (Polanyi 1974), procedural knowledge (Squire 1986) and practical knowledge (Van Der Steen and Sloep 1993). These varied concepts may be describing the same phenomenon—an axiom of the embodied cognition research programme assumes that concepts are not purely propositional in form, but involve information drawn from the sensorimotor and perceptual systems (Barsalou 2008; Mahon and Caramazza 2008). Non-propositional knowledge is inarticulable because it has been developed through the motor or perceptual system and is not encoded in a symbolic form. For example, an expert scientist's concept of magnetism may involve a range of types of knowledge, some propositional, such as the fact that like poles repel, and some non-propositional, for example, the sensation of two poles repelling or mental images of the three-dimensional magnetic field produced by a bar magnet. Whilst the nature of the link between abstract symbols and sensorimotor experiences is far from settled, there is a growing body of evidence that supports the notion that cognition involves more than just propositional knowledge (Galetzka 2017). This article considers the value of non-propositional knowledge in learning about science.

To argue for the value of non-propositional knowledge in science education does not diminish the importance of propositional knowledge. Students need to acquire scientific propositional knowledge in order to participate in the work of the community of scientists (Lave and Wenger 1991). However, scientific knowledge does not consist solely of propositional knowledge (diSessa 1993); for example, an understanding of force will involve both propositional knowledge, such as Newton's laws, but also non-propositional knowledge, for example, embodied knowledge of the experience of acceleration. Henderson and Horgan (2000) described an 'ice-berg epistemology' in which propositional knowledge is only a subset, the tip of the iceberg, of the epistemological elements that make up the totality of a concept. Propositional knowledge is an important part of the knowledge generated by scientists, and the acquisition of such knowledge is a necessary and valuable goal of school science. However, we argue that gaining propositional knowledge should not be the only goal of science education and examine approaches to supporting students' development of non-propositional knowledge.

Whilst the value of non-propositional knowledge in developing scientific understanding has been emphasised by a number of researchers (Brock 2015; diSessa 1993; Nola and Irzik 2005; Wellington and Ireson 2012), recently, a movement in the USA, the UK and elsewhere has argued for the priority of propositional knowledge in curricula (Hirsch 2016; Starmans and Friedman 2012; Willingham 2009; Young 2008). Hirsch (2006) argued that in US schools, reduced attention on knowledge in curricula had led to impoverished educational experiences, and proposed curricula that specify in detail the content knowledge to be taught. In the UK, Michael Young (2008) has suggested that a clear distinction can be made between everyday and theoretical knowledge and argued that curricula focused on theoretical knowledge acquisition can promote social justice. These thinkers have influenced policy makers on both sides of the Atlantic (Gibb 2017; Kerslake and Wegerif 2018) leading to the development of knowledge-based curricula that specify, in detail, the propositions to be learned (e.g. Hirsch et al. 2014). At a time when there is a renewed emphasis on knowledge acquisition, it is an opportune moment to address the claim that it is possible to gain considerable propositional scientific knowledge without understanding (Kosso 2002; Toulmin 1961; Zagzebski 2001) and to emphasise that the work of scientists draws on both propositional and non-propositional knowledge (Collins 2010).

This article considers a thought experiment, Mary's Room, proposed by Frank Jackson (1982), that raises the question of whether propositional knowledge can provide a complete account of scientific phenomena. The thought experiment is applied to the context of science education and it is asserted that science learners' experiences of objects and phenomena lead to the acquisition of knowledge that is distinct from propositional knowledge, and, in addition, that such knowledge is valuable for developing scientific understanding.

2 Mary's Room and the Knowledge Argument

2.1 The Knowledge Argument

A number of epistemologists, including those discussed in this section, have addressed the question of whether the possession of complete propositional knowledge gives complete knowledge of a phenomenon. Broad (1925) imagined a 'mathematical archangel' with the power to directly perceive the microscopic structure of matter. For example, when learning

about ammonia, Broad argued that the archangel's ability would lead to knowledge of how the compound reacts with other molecules and how it would interact with the human olfactory system. However, the archangel powers would, Broad claimed, be deficient in one aspect—the archangel would not be capable of developing knowledge of what humans experience when they smell ammonia. The thought experiment raises the question of whether a student who can state that ammonia has a pungent smell, but has never directly experienced the compound's distinct odour, has complete knowledge of the smell of ammonia. Eddington (1948) imagined a Martian observer watching an armistice ceremony on Earth and claimed that the alien spectator, lacking the ability to feel compassion or pity, could not develop full knowledge of the event. Some forms of innate knowledge, Eddington concluded, cannot be represented by symbols. The Martian argument is restated in Nagel's (1974) paper 'What is it like to be a bat?' Nagel argues that whilst an alien scientist might come to understand the phenomenon of rainbows, they could not acquire the human concept of rainbows because the concept is entwined with a particular point of view, that of a human observer.

Whilst the previous examples involve a non-human observer, the Mary's room thought experiment, proposed by Frank Jackson (1982), involves a human perceiver. Jackson described a brilliant scientist, Mary, who is required to investigate the world from inside a black-and-white room, using a monochrome video link. Mary is a specialist in the neurophysiology of vision and acquires all the physical information that it is possible to know about visual perception. In particular, she learns about the process of seeing a red tomato and acquires knowledge of the distribution of wavelengths involved and the processes that occur in the retina, optic nerve and brain to produce the phenomenal experience. Jackson (1986, p. 291) assumed that Mary knows all the 'physical facts' about the experience of seeing a tomato, that is, all the relevant physical, biological and neurological propositional knowledge and asks whether Mary will learn anything if, when released from the room, she sees a red tomato for the first time. He argued that, though Mary knows all the physical facts related to colour vision before her release, she gains some additional information on seeing the tomato and, hence, that not all information is information about the physical world. This reasoning has been labelled the knowledge argument (Georgiev 2018) and led Jackson, in his 1986 article, to reject physicalism, the view that everything is physical and that all facts and properties are facts about physical entities or their properties (Kallestrup 2006). Some 20 years after proposing the thought experiment, Jackson (2003) changed his stance and reported that he had become convinced by arguments for physicalism.

2.2 Responses to the Knowledge Argument

Since its publication, Jackson's (1982) thought experiment has prompted a number of responses. The replies can be categorised as follows (Van Gluick 2004):

- a) *Mary gains no additional knowledge on seeing the tomato.* Dennett (1991) argued that the intuition that Mary gains knowledge is mistaken and arises because it is hard to conceptualise what the possession of complete physical knowledge entails. When Mary encounters the tomato, she may feel a sense of recognition but she does not gain new knowledge (Churchland 1985; Hardin 1988).
- b) *Mary gains new propositional knowledge.* Some critics, for example, Stanley and Williamson (2001), deny a distinction between types of knowledge and assert that all

knowledge is propositional knowledge. Hence, the knowledge that Mary gains on her release is more propositional knowledge.

- c) *Mary gains new propositional knowledge but does not come to know any new propositions.* A variation on the previous response proposes that Mary acquires new propositional knowledge, for example, knowledge of the phenomenon of redness, but this knowledge is a reconceptualisation of knowledge Mary possessed whilst in the room (Horgan 1984; Tye 1986).
- d) *Mary gains new non-propositional knowledge.* Mary has been described as gaining a number of different types of non-propositional knowledge when she encounters the tomato, two of which are discussed here. First, it is argued that, on observing the tomato, Mary gains an ability that she did not possess before leaving the room (Lewis 1990, 2003; Nemirow 1980, 1990). Nemirow (1990) associated such knowledge with the ability to imagine an experience. On encountering the tomato, Mary gains the ability to fully imagine the fruit—knowledge she did not possess before the encounter. The ability hypothesis has been critiqued on the grounds that it is possible to lack the ability to imagine an experience, yet still know what it is like (Alter 1998; Conee 1994). Second, the acquaintance model proposes a class of knowledge in addition to propositional knowledge and knowledge-how, acquaintance knowledge (Conee 1994), which is acquired through familiarity with an entity in the most direct way possible.

In parallel to the debate about the nature of the knowledge that Mary may gain, a number of criticisms of Jackson's thought experiment have been raised. Horgan (1984) pointed out that Jackson's response to the thought experiment conflates two arguments—an ontological assertion that non-physical facts exist and an epistemological claim that Mary gains new knowledge that need not be ontologically different from the knowledge she already possesses. The second argument proposes that whilst Mary begins with a complete physical account of perception, this need not mean she possesses all the ontologically physical information about the tomato and its properties. Hence, the knowledge Mary gains is novel ontologically physical information about phenomenal redness. Horgan (1984) concluded that there is no need to reject physicalism if it is assumed that Mary learns something new on seeing the tomato. This epistemological argument is of relevance to science education as it moves discussion away from the ontology of knowledge and raises two significant questions: (a) Does first-hand experiential engagement lead to knowledge in addition to propositional knowledge? (b) Is what is gained by direct experience of objects of value for learners' scientific education? These questions may be placed in context by considering an adaptation of Jackson's thought experiment to the classroom.

2.3 The Knowledge Argument in the Classroom

Imagine a classroom in which a student, Mary, is learning about magnetism. She is taught all the available propositional knowledge related to the nature of magnetic force. Mary is tested and gives the correct responses to questions about the way in which magnets behave. However, her teacher chooses to deny Mary first-hand experiences of magnetic forces. Assuming she has had no previous encounters with magnets outside of the classroom, first, does Mary gain knowledge when she first holds two magnets and experiences the force that acts as she brings them together? Second, if she gains something through the experience, is what is gained of value in the context of science education? Teachers' responses to this thought

experiment will have consequences for their pedagogy. An educator who argues that Mary's education, though complete in respect to propositional knowledge, is lacking in some phenomenological manner (Sheets-Johnstone 2011), will value and encourage experiential engagement. By contrast, a teacher who believes that Mary does not gain anything of pedagogical value from her experience with magnets might argue that students can acquire scientific expertise solely by learning the appropriate propositional knowledge. In this article, we make the case that there is valuable knowledge to be gained in addition to propositional knowledge of scientific concepts and teachers should arrange, as far as is practically possible, for students to gain direct experience of the objects and phenomena described in science curricula. The epistemological aspect of Jackson's (1982) original argument is thus accepted—it is argued that Mary gains new, non-propositional knowledge on encountering magnets for the first time.

To argue for the value of non-propositional knowledge in science education, first, we make the case that propositional and non-propositional knowledge are distinct. Writing in the middle of the twentieth century, Ryle (1945) reported, and critiqued, the prevailing doctrine, labelled intellectualism, which argued that intelligence was related only to propositional knowledge. Writers who argue that the aim of education is primarily knowledge acquisition and imply that knowledge is purely propositional (e.g. Gibb 2015; Hirsch 2016; Yandell 2017) endorse the intellectualist position. Though intellectualist positions may take stronger and weaker forms (Glick 2011), their proponents deny that a distinction exists between knowledge-how and knowledge-that and argue that all knowledge reduces to propositional knowledge (Stanley and Williamson 2001). By contrast, anti-intellectualists argue for a separation between propositional knowledge and knowledge-how (Habgood-Coote 2018). Anti-intellectualism is widely accepted by epistemologists (Stanley and Williamson 2001) and coheres with how people typically think about knowing (Harmon and Horne 2016). A body of research in cognitive science and neuropsychology supports the distinction between knowledge-how and knowledge-that (Adams 2009; Glick 2011; Wallis 2008). The anti-intellectualist hypothesis is reinforced by data that suggest that expert behaviour is not easily replicated by computer programmes coded to draw on the propositional knowledge possessed by experts in a domain and hence, it is argued, expertise requires more than knowledge of propositions (Dreyfus 1972; Glick 2011), as well as by evidence that declarative and procedural memory are distinct (Cohen and Squire 1980; Martone et al. 1984). To take one example, expert clinicians can make correct judgements whilst holding false beliefs about the methods that they used to reach their conclusions (Wallis 2008). We therefore assume that propositional and non-propositional knowledge are distinct.

Second, we assert that even though Mary had learned all the available propositional knowledge related to magnetism before she first encounters magnets, she gains additional knowledge when she first experiences magnetic forces and that additional knowledge has a non-propositional form. All the propositional information that Mary had studied cannot help her know what it is like to move two magnets close together. The experience brings something else (Lewis 2003), such as enrichment of her concept of magnetic force with information from the sensorimotor system, for example, the sensation of two poles repelling. As argued below, such non-propositional knowledge can become part of an expert mental model and allow Mary to predict how other magnetic systems will behave (Franco and Colinviaux 2000). Experience has an irreducible quality that cannot be represented in propositional form (Harman 1990). Mary's first-hand engagement with magnetic attraction and repulsion affords knowledge that she cannot acquire by learning all the available propositional statements related to

electromagnetic interactions. If the assumption that Mary gains non-propositional knowledge through engagement with objects and phenomena is accepted, it might still be argued that, if it assumed that perceptual and propositional scientific knowledge are distinct (Schier 2008), science education should concern itself only with propositional knowledge and that non-propositional knowledge is of limited value in learning science. The next section develops a case that non-propositional knowledge is a valuable aspect of scientific knowing.

3 The Value of Non-propositional Knowledge in the Work of Scientists and in Science Education

Non-propositional knowledge can be considered a valuable epistemic state because it enables autonomous action (Markie 2019), can spur confident responses (Carter and Poston 2018) and is a cognitive achievement that arises from the exercise of non-accidental abilities (Carter and Pritchard 2015). In particular, non-propositional knowledge has been argued to be a valuable aspect of scientific knowing (Collins 2010; Shapiro and Stolz 2019; Weisberg and Newcombe 2017) and hence also science education (Brock 2015, 2017; Taber 2014). Some arguments for the value of non-propositional scientific knowledge have focused on its use in the production of new scientific concepts (Polanyi 1966/2009; Ryle 1945), what might be considered as the context of discovery (Reichenbach 1938). Scientists, Ryle (1945) suggested, are primarily knowers-how, as the process of developing novel conceptual knowledge requires knowledge-how, that is, knowledge of the processes of discovery. It might be argued that, whilst non-propositional knowledge plays a role in the work of research scientists, school science takes place in the context of justification in which the acquisition of propositional knowledge is the major goal. This view presents an overly narrow understanding of the role of non-propositional knowledge in cognition.

Psychological concepts are not composed solely of propositional statements but draw on both propositional and non-propositional elements (Barsalou 2008; Henderson and Horgan 2000; Sartwell 1991). The embodied cognition research programme takes as axiomatic that cognition involves the sensory and motor systems (Hayes and Kraemer 2017; Johnson-Glenberg et al. 2016; Sullivan 2018). Therefore, concepts are not solely abstracted propositions but are embedded in sensory modalities, for example, visual or tactile modes (Hayes and Kraemer 2017; Hsu et al. 2012; Martin 2016). At least some of a scientist's knowledge exists in the form of non-propositional knowledge such as images or muscle memories of sensations (Reiner 1998). Such somatic tacit knowledge (Collins 2010) is gained by learning how to carry out actions, for example, in learning how to use a piece of practical equipment. In addition, collective tacit knowledge (Collins 2010) may be acquired through engagement in the practices of an expert social group, for example, a group of scientists. For example, Collins (1985) has reported that the process of building a laser from plans requires the transfer of non-propositional knowledge between researchers.

Cognition can be modelled as consisting of many components including both propositional scientific knowledge and phenomenological knowledge that is inarticulate, lacks propositional form and acts as a sense of mechanism that explains events in the world (diSessa 1993, 2002, 2008). For example, Ohm's phenomenological primitive (or p-prim) is knowledge that the more effort that is expended, the greater the result and conversely, the greater the resistance, the more the effort that is required (diSessa 2000). Learners may then argue that, for example, greater pressure leads to faster fluid flow without being able to articulate the justification for

their argument because the phenomenological knowledge used is non-propositional. It is argued that p-prims are not discarded as learners develop expertise, but rather that their activation and suppression within a wider conceptual structure is tuned to match that of experienced scientists (diSessa 1993).

Non-propositional knowledge is not just a desirable but unnecessary appendage to propositional knowledge, but acts as the foundation of expert understanding (Collins 2010; diSessa 1993). If the hypothesis that appropriate non-propositional knowledge is beneficial is to be accepted, evidence needs to be presented that students' achievement in science (typically measured using questions drawn from past standardised science tests) can be supported by exposing them to activities that do not increase their propositional knowledge. A growing body of evidence that achievement in science correlates with spatial ability for learners of different ages (Hodgkiss et al. 2018; Wai et al. 2009) provides evidence of the role of non-propositional knowledge in scientific understanding. A meta-analysis of intervention studies suggests that spatial skills, and therefore scientific achievement, can be improved through practice, using activities that do not involve propositional knowledge acquisition (Uttal et al. 2012). This observation can be explained by the body of research that reports that students make use of sensorimotor simulation in both reasoning and problem-solving (Wilson 2002). Knowledge in the science classroom should be conceptualised as including not only propositional statements but also non-propositional elements such as perceptual and sensorimotor information (Goldstone et al. 2008). A number of studies, discussed in the next section, present evidence that engagement with activities that develop non-propositional knowledge can support students' scientific understanding.

4 Strategies to Develop Students' Non-propositional Scientific Knowledge

Collins (2013, p. 27) has argued that whilst people can exchange propositional knowledge relatively straightforwardly, as it can be 'broadcast' and transferred through texts, non-propositional knowledge, by contrast, is more challenging to share. For example, knowledge of how to apply propositional knowledge to different contexts may draw on non-propositional knowledge of the salient features of situations that is challenging to transfer to students (Hammer et al. 2005). If, as has been argued, the acquisition of appropriate non-propositional knowledge is an aspect of scientific understanding, educators should make use of approaches that develop students' non-propositional knowledge. Researchers in science education have proposed a number of strategies for supporting students' non-propositional knowledge, which are grouped into two categories: practical work and technologically enhanced activities.

4.1 Practical Work

Activities in which students 'observe and/or manipulate the objects or materials they are studying' (Millar 2010, p. 109, italics removed) are referred to as practical work and are considered a potentially valuable aspect of scientific education (Holman 2017). Note that practical work is taken to include experiences in a range of settings, including outdoor education and informal education in museums, where students observe or manipulate objects (Ayotte-Beaudet et al. 2017; Braund and Reiss 2006). A number of purposes of practical work

have been proposed (Beatty and Woolnough 1982; Hodson 1990; Kerr 1963; Nott and Wellington 1996), including to foster careful observation, to develop manipulative skills, to promote interest and motivation, to give actual experience of scientific phenomena, to develop problem-solving skills and to verify facts and principles taught. Whilst the usefulness of practical work for supporting the acquisition of propositional knowledge has been much debated (Abrahams and Millar 2008), the role of these activities in developing non-propositional knowledge has received less attention. As argued above, non-propositional knowledge may take the form sensorimotor information and the acquisition of such knowledge may support students' understanding of scientific concepts. For example, as described below, researchers have found that directly experiencing the sensation of twisting the axle of a spinning bicycle wheel can improve students' understanding of conservation of angular momentum (Kontra et al. 2015).

It is important that teachers and students are clear about the purposes of practical work in science classrooms (Hofstein and Lunetta 2004). When the aim of a practical activity is misunderstood, its value can be diminished (Abrahams and Millar 2008; Hodson 1991). Research suggests that students too rarely learn propositional scientific knowledge from doing practical work (Abrahams and Millar 2008; Abrahams and Reiss 2017) and that students may then come to view practical activities as an exercise in procedure following (Clough 2006). As an alternative, it is useful to emphasise that a purpose of practical work is the acquisition of non-propositional knowledge. For example, in an activity in which students swing an object on a string in a circle, they might be told that they are carrying out the practical to directly experience centripetal force. Such conceptualisation may not only enrich students' knowledge of scientific concepts but also support their development of a model of the nature of science that acknowledges that scientists use both propositional and non-propositional knowledge in their work (Collins 2010).

It has been argued that scientific knowing includes 'a component that is experience-dependent in a very personal sense' and therefore 'not directly teachable' (Hodson 1993, p. 120). Practical work allows students to experience 'the touch and feel' (Wellington and Osborne 2001, p. 7) of objects that cannot be gained by learning propositional knowledge alone. Engagement with physical objects has been described as 'thinking with the hands' (Latour 1986) and is conceptualised as leading to 'knowledge of the hands' (Merleau-Ponty 2005) that cannot be directly expressed in words. Elgin (2017) has argued that a learner can understand a scientific concept even if they lack the ability to explain it explicitly. For example, Lipton (2009) has described how his understanding of the retrograde motion of Mars was supported by viewing an orrery and he argued that understanding may, in some contexts, occur without the ability to formulate an explanation. In a similar way, diSessa's (1993) description of p-prims suggests that learners develop an inarticulate sense of mechanism that can act both as a hindrance to the acquisition of scientific ideas but also form part of expert understanding. An emerging research programme based on the assumptions of embodied cognition has begun to provide evidence for the claim that practical work develops valuable non-propositional knowledge (Kontra et al. 2015). Kontra and colleagues (2015) demonstrated that giving students a brief opportunity to experience first-hand the conservation of angular momentum by trying to rotate the axle of a spinning bicycle wheel improved performance on a test of propositional knowledge. Future research should investigate the kinds of practical activities that are most supportive of conceptual understanding in different contexts and how such

activities are best structured to facilitate the development of links between propositional and non-propositional knowledge.

4.2 Technologically Enhanced Activities

Interactive digital simulations have been suggested as technologies that may support students' development of non-propositional knowledge (Black 2010; diSessa 1986; Swaak and de Jong 1996). For example, a simulation of the motion of an object in a drag-free environment allows students to experience a context they are otherwise unlikely to encounter, and thus supports the development of their phenomenological knowledge (diSessa 1986). Recently developed technologies present novel opportunities for helping students to acquire non-propositional knowledge. Haptics, technology that allows computer systems to give feedback via the sense of touch (Brooks et al. 1990; Han and Black 2011; Minogue and Jones 2006; Reiner 1999), may be used to support students' non-propositional learning. For example, a tactile interface has been used to allow learners to experience forces as though their hand were immersed in a field (Reiner 1999). Learners who lacked formal training in physics were able to construct representations of field lines similar to those produced by experts using the interface, demonstrating that non-propositional knowledge can act as foundation for propositional scientific knowledge.

In the three contexts discussed below, teaching about centripetal motion, vectors and levers, teachers often make use of practical work to support students' acquisition of non-propositional knowledge. However, new technologies can be used to promote bodily engagement and make explicit the links between sensations and scientific concepts. Johnson-Glenberg, Megowan-Romanowicz and their team (Johnson-Glenberg and Megowan-Romanowicz, 2017, Johnson-Glenberg et al. 2016) have trialled two approaches to supporting the development of students' non-propositional knowledge in the context of learning about science. They have studied an immersive environment (SMALLab) that uses motion capture and data projection to teach about centripetal motion (Johnson-Glenberg et al. 2016). The environment allows information, such as the trajectory of an object released from circular motion, to be projected onto the ground. When they compared learning gains from environments with different degrees of immersion, the researchers found that there were no significant differences in learning gains on an immediate post-test of students taught in the different conditions. However, one week after teaching, the students who had been exposed to more immersive environments performed better on tests of knowledge of circular motion than students taught in less immersive environments.

The researchers subsequently trialled an approach in which a motion capture sensor enabled students to draw vectors using gestures (Johnson-Glenberg and Megowan-Romanowicz 2017) and reported significant learning gains for students who used the approach in comparison with those who were taught using symbols and text. Interventions that support the development of non-propositional knowledge need not have high levels of technological complexity. Pouw and colleagues (2016) compared the effects of teaching about levers using two types of animations of seesaws, one which showed only the lever and a second which had the silhouette of a body with its arms outstretched to align with the seesaw superimposed. The arms of the body moved with the seesaw. They reported that students who saw the animations with the body analogy showed improved lever problem-solving accuracy in comparison with students who were shown the simpler animations.

5 Conclusions—Towards a Phenomenological Curriculum

The acquisition of scientific knowledge is an important aim of science education (Hodson 1985; Smith and Siegel 2004, 2016). The studies described above suggest that, in addition to propositional knowledge, non-propositional knowledge is a significant component of scientific expertise. To return to the classroom example introduced earlier, Mary, the student learning about magnetism, can be conceptualised as gaining non-propositional knowledge that is significant for her scientific understanding when she is allowed to experience the forces that act between magnetic poles for the first time. The focus of teaching and assessment in science classrooms, however, is often largely on propositional knowledge (Sinatra et al. 2003). Recent curriculum reforms in the USA and the UK have led to adoption of 'knowledge-based' curricula (Gibb 2015; Hirsch 2016; Yandell 2017) that assume that the knowledge students should acquire can be represented as series of statements. We have argued that scientific concepts involve both propositional and non-propositional knowledge (Barsalou 2008; diSessa 1993; Henderson and Horgan 2000), so a curriculum that prioritises propositional knowledge and neglects to develop students' non-propositional knowledge will leave students with incomplete understanding (Belas 2017). There is a danger that school science classrooms can function like Mary's room. Students are supported to learn much propositional knowledge but with limited direct experience of scientific phenomena and objects. Whilst acquiring propositional knowledge is an important part of science education, science teaching should aim to develop a rounded understanding that is built on both propositional and non-propositional knowledge (Brock 2018a, 2018b).

By contrast to the focus on propositional knowledge in some curricula for older learners, the value of direct experiences of phenomena is emphasised in several curricula for younger learners. For example, in the national curriculum for key stage 2 (learners aged 7–11 years) in England, there is a non-statutory requirement that learners 'should experience forces that make things begin to move, get faster or slow down' (DfE 2013, p. 30). Similar guidance is lacking from programmes of study for older learners. A specification of the kinds of experiences that would develop students' non-propositional knowledge would be useful additions to curricula for all ages. The notion of a phenomenal curriculum is not a new concept. A specification of a series of experiences as a necessary part of training is an implicit assumption of apprenticeships (Hutchings and Wutzdorff 1988) and writers have long emphasised the importance of learning through first-hand experience of phenomena (Dewey 1903; Froebel 1898/2005; Kolb 2015). Whilst curricula often contain detailed specification of propositional knowledge, similar guidance on non-propositional knowledge is often lacking.

By definition, describing non-propositional knowledge is challenging but the notion of phenomenal concepts (Loar 1990; Stoljar 2005), representations of physical or sensory experience, for example, *sensation of red*, may be helpful. For example, consider a typical physics learning objective: 'explain that inertia is a measure of how difficult it is to change the velocity of an object and that the mass is defined as the ratio of force over acceleration' (OCR 2018, p. 23). If a learner can state the definition of inertia, and the equation linking force and acceleration, they might be assumed to possess the required propositional knowledge. However, teachers should also consider the phenomenal concepts that contribute to a student's understanding of inertia, for example, the *sensation of acceleration* and the *sensation of travelling at constant velocity*. The experiential curriculum might suggest that students (a) experience attempts to accelerate high and low mass objects and (b) experience the motion of an object in a low friction

environment (e.g. an ice hockey puck sliding over ice or a slider on an air track). The research programme described above has already begun to report the kinds of experiences that can support learning in different topics on the science curriculum. The phenomenal curriculum should be developed through empirical research, as in the Kontra et al. (2015) study of students' learning gains after experiencing a spinning wheel, that reports the kinds of experiences that support students' scientific understanding.

Through direct experience of objects, for example, feeling the changing forces in the string of an object swung in a circle, learners gain knowledge that is not expressible as propositional knowledge (Winch 2013). Whilst non-propositional knowledge can cause misconceptions, appropriately applied, it may also be the basis of expert understanding (diSessa 1993). Educators must strive to ensure that their learners avoid the thin educational experiences of Mary's classroom in which they come to know all the facts but have experienced little and present learners with first-hand experiences of scientific objects and phenomena that develop their non-propositional knowledge.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Abrahams, I., & Millar, R. (2008). Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science. *International Journal of Science Education*, 30(14), 1945–1969.
- Abrahams, I., & Reiss, M. J. (2017). How to use this book. In I. Abrahams & M. J. Reiss (Eds.), *Enhancing learning with effective practical science 11–16* (pp. 1–3). London: Bloomsbury Academic.
- Adams, M. P. (2009). Empirical evidence and the knowledge-that/knowledge-how distinction. *Synthese*, 170(1), 97–114.
- Aikenhead, G. S. (1996). Science education: Border crossing into the subculture of science. *Studies in Science Education*, 27(1), 1–52.
- Alter, T. (1998). A limited defense of the knowledge argument. *Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition*, 90(1), 35–56.
- Aristotle. (2014). In R. Crisp (Ed.), *Nicomachean ethics*. Cambridge: Cambridge University Press.
- Ayotte-Beaudet, J.-P., Potvin, P., Lapierre, H. G., & Glackin, M. (2017). Teaching and learning science outdoors in schools' immediate surroundings at K-12 levels: a meta-synthesis. *EURASIA Journal of Mathematics, Science and Technology Education*, 13(8), 5343–5363.
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59(1), 617–645.
- Beatty, J. W., & Woolnough, B. E. (1982). Practical work in 11-13 science: the context, type and aims of current practice. *British Educational Research Journal*, 8(1), 23–30.
- Belas, O. (2017). On tacit knowledge for philosophy of education. *Studies in Philosophy and Education*, 37(4), 347–365.
- Bigelow, J. (2006). Gettier's theorem. In S. Hetherington (Ed.), *Aspects of knowing: Epistemological essays* (pp. 203–218). Oxford: Elsevier Ltd..

- Black, J. B. (2010). An embodied/grounded cognition perspective on educational technology. In M. S. Khine & I. Saleh (Eds.), *New science of learning: Cognition, computers and collaboration in education* (pp. 45–52). New York: Springer.
- Braund, M., & Reiss, M. (2006). Towards a more authentic science curriculum: the contribution of out-of-school learning. *International Journal of Science Education*, 28(12), 1373–1388.
- Broad, C. D. (1925). *The mind and its place in nature*. London: Routledge & Kegan Paul Ltd..
- Brock, R. (2015). Intuition and insight: two concepts that illuminate the tacit in science education. *Studies in Science Education*, 51(2), 127–167.
- Brock, R. (2017). Tacit knowledge in science education: the role of intuition and insight in teaching and learning science. In K. S. Taber & B. Akpan (Eds.), *Science education. An international course companion* (pp. 133–142). Rotterdam: Sense Publishers.
- Brock, R. (2018a). Knowing is only the first step: strategies to support the development of scientific understanding. *School Science Review*, 99(369), 119–124.
- Brock, R. (2018b). Lucky belief in science education: Gettier cases and the value of reliable belief-forming processes. *Science & Education*, 27(3–4), 247–258.
- Brooks, F. P., Ouh-Young, M., Batter, J. J., Jerome Kilpatrick, P., Brooks Jr., F. P., Ouh-Young, M., & Jerome Kilpatrick, P. (1990). Project GROPE: Haptic displays for scientific visualization. In *In Proceedings of the 17th annual conference on Computer graphics and interactive techniques - SIGGRAPH '90* (Vol. 24, pp. 177–185). New York: ACM Press.
- Carter, J. A., & Poston, T. (2018). *A critical introduction to knowledge-how*. London: Bloomsbury Academic.
- Carter, J. A., & Pritchard, D. (2015). Knowledge-how and cognitive achievement. *Philosophy and Phenomenological Research*, 91(1), 181–199.
- Churchland, P. M. (1985). Reduction, qualia, and the direct introspection of brain states. *The Journal of Philosophy*, 82(1), 8–28.
- Clough, M. P. (2006). Learners' responses to the demands of conceptual change: considerations for effective nature of science instruction. *Science & Education*, 15(5), 463–494.
- Cohen, N. J., & Squire, L. R. (1980). Preserved learning and retention of pattern-analyzing skill in amnesia: dissociation of knowing how and knowing that. *Science*, 210(4466), 207–210.
- Collins, H. (1985). *Changing order: replication and induction in scientific practice*. Beverly Hills: Sage.
- Collins, H. (2010). *Tacit and explicit knowledge*. Chicago: University of Chicago Press.
- Collins, H. (2013). Building an antenna for tacit knowledge. *Philosophia Scientiae*, 17(3), 25–39.
- Conee, E. (1994). Phenomenal knowledge. *Australasian Journal of Philosophy*, 72(2), 136–150.
- Dennett, D. C. (1991). *Consciousness explained*. Boston: Little, Brown and Company.
- Department for Education. (2013). *Science programmes of study: key stages 1 and 2*. London: Department for Education.
- Dewey, J. (1903). Democracy in education. *The Elementary School Teacher*, 4(4), 193–204.
- diSessa, A. A. (1986). Artificial worlds and real experience. *Instructional Science*, 14(3–4), 207–227.
- diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10(2–3), 105–225.
- diSessa, A. A. (2000). *Changing minds: computers, learning, and literacy*. Cambridge: MIT Press.
- diSessa, A. A. (2002). Why “conceptual ecology” is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: issues in theory and practice* (pp. 29–60). Dordrecht, Boston: Kluwer.
- diSessa, A. A. (2008). A bird's-eye view of the “pieces” vs. “coherence” controversy (from the “pieces” side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (1st ed., pp. 35–60). New York, Routledge.
- Dreyfus, H. (1972). *What computers can't do*. New York: Harper & Row.
- Eddington, S. A. (1948). *The nature of the physical world*. Cambridge: Cambridge University Press.
- Elgin, C. Z. (2017). *True enough*. Cambridge: MIT Press.
- Franco, C., & Colinaux, D. (2000). Grasping mental models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 93–118). Dordrecht: Kluwer Academic Publishers.
- Frebel, F. (1898). *The education of man*. Mineola: Dover Publications, Inc.
- Galetzka, C. (2017). The story so far: how embodied cognition advances our understanding of meaning-making. *Frontiers in Psychology*, 8(1315), 1–5.
- Georgiev, D. D. (2018). *Quantum information and consciousness: a gentle introduction*. Boca Raton: CRC Press.
- Gettier, E. L. (1963). Is justified true belief knowledge? *Analysis*, 23(6), 121–123.
- Gibb, N. (2015). How E. D. Hirsch came to shape UK government policy. In J. Simons & N. Porter (Eds.), *Knowledge and the curriculum. A collection of essays to accompany E. D. Hirsch's lecture at policy exchange* (pp. 12–20). London: Policy Exchange.

- Gibb, N. (2017). *The importance of knowledge-based education. Speech at the launch of the "The Question of Knowledge", 19th October 2017*. London: DfE.
- Girod, M., Rau, C., & Schepige, A. (2003). Appreciating the beauty of science ideas: teaching for aesthetic understanding. *Science Education*, 87(4), 574–587.
- Glick, E. (2011). Two methodologies for evaluating intellectualism. *Philosophy and Phenomenological Research*, 83(2), 398–434.
- Goldstone, R., Landy, D., & Son, J. Y. (2008). A well grounded education: the role of perception in science and mathematics. In M. DeVega, A. M. Glenberg, & A. C. Graesser (Eds.), *Symbols and embodiment: debates on meaning and cognition* (pp. 327–355). New York: Oxford University Press.
- Habgood-Coote, J. (2018). Knowledge-how, abilities, and questions. *Australasian Journal of Philosophy*, 97(1), 86–104.
- Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In J. Maestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 89–120). Greenwich: Information Age Publishing.
- Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education*, 57(4), 2281–2290.
- Hardin, C. L. (1988). *Colour for philosophers*. Indianapolis: Hackett Publishing Company.
- Harman, G. (1990). The intrinsic quality of experience. *Philosophical Perspectives*, 4, 31–52.
- Harmon, I., & Horne, Z. (2016). Evidence for anti-intellectualism about know-how from a sentence recognition task. *Synthese*, 193(9), 2929–2947.
- Hayes, J. C., & Kraemer, D. J. M. (2017). Grounded understanding of abstract concepts: the case of STEM learning. *Cognitive Research: Principles and Implications*, 2(7), 1–15.
- Henderson, D., & Horgan, T. (2000). Iceberg epistemology. *Philosophy and Phenomenological Research*, 61(3), 497–535.
- Hetherington, S. (2011). The Gettier problem. In S. Bernecker & D. Pritchard (Eds.), *The Routledge companion to epistemology* (pp. 119–130). New York, NY: Routledge.
- Hirsch, E. D. (2006). *The knowledge deficit*. Boston: Houghton Mifflin Company.
- Hirsch, E. D. (2016). *Why knowledge matters: rescuing our children from failed educational theories*. Cambridge: Harvard University Press.
- Hirsch, E. D., Whelan, R., & Lubicz-Nawrocka, T. (2014). *What your year 6 child needs to know: fundamentals of a good year 6 education*. London: Civitas.
- Hodgkiss, A., Gilligan, K. A., Tolmie, A. K., Thomas, M. S. C., & Farran, E. K. (2018). Spatial cognition and science achievement: the contribution of intrinsic and extrinsic spatial skills from 7 to 11 years. *British Journal of Educational Psychology*, 88(4), 675–697.
- Hodson, D. (1985). Philosophy of science, science and science education. *Studies in Science Education*, 12(1), 25–57.
- Hodson, D. (1990). A critical look at practical work in school science. *School Science Review*, 70(256), 33–40.
- Hodson, D. (1991). Practical work in science: time for a reappraisal. *Studies in Science Education*, 19(1), 175–184.
- Hodson, D. (1993). Re-thinking old ways: towards a more critical approach to practical work in school science. *Studies in Science Education*, 22(1), 85–142.
- Hodson, D. (2010). Science education as a call to action. *Canadian Journal of Science, Mathematics and Technology Education*, 10(3), 197–206.
- Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: foundations for the twenty-first century. *Science Education*, 88(1), 28–54.
- Holman, J. (2017). *Good practical science*. London: Gatsby Charitable Foundation.
- Horgan, T. (1984). Jackson on physical information and qualia. *The Philosophical Quarterly*, 34(135), 147–152.
- Hsu, N. S., Frankland, S. M., & Thompson-Schill, S. L. (2012). Chromaticity of color perception and object color knowledge. *Neuropsychologia*, 50(2), 327–333.
- Hutchings, P., & Wutzdorff, A. (1988). Experiential learning across the curriculum: assumptions and principles. *New Directions for Teaching and Learning*, 1988(35), 5–19.
- Jackson, F. (1982). Epiphenomenal Qualia. *The Philosophical Quarterly*, 32(127), 127–136.
- Jackson, F. (1986). What Mary didn't know. *The Journal of Philosophy*, 83(5), 291–295.
- Jackson, F. (2003). Mind and illusion. *Royal Institute of Philosophy Supplement*, 53, 251–271.
- Johnson-Glenberg, M. C., & Megowan-Romanowicz, C. (2017). Embodied science and mixed reality: how gesture and motion capture affect physics education. *Cognitive Research: Principles and Implications*, 2(24), 1–28.
- Johnson-Glenberg, M. C., Megowan-Romanowicz, C., Birchfield, D. A., & Savio-Ramos, C. (2016). Effects of embodied learning and digital platform on the retention of physics content: centripetal force. *Frontiers in Psychology*, 7(1819), 1–22.

- Kallestrup, J. (2006). Epistemological physicalism and the knowledge argument. *American Philosophical Quarterly*, 43(1), 1–23.
- Kerr, J. (1963). *Practical work in school science*. Leicester: Leicester University Press.
- Kerslake, L., & Wegerif, R. (2018). Introduction. In L. Kerslake & R. Wegerif (Eds.), *Theory of teaching thinking: International perspectives* (pp. 1–10). Abingdon: Routledge.
- Kind, P., & Osborne, J. (2017). Styles of scientific reasoning: a cultural rationale for science education? *Science Education*, 101(1), 8–31.
- Klein, P. (1971). A proposed definition of propositional knowledge. *The Journal of Philosophy*, 68(16), 471–482.
- Kolb, D. A. (2015). *Experiential learning: experience as the source of learning and development*. Upper Saddle River: Pearson Education Ltd..
- Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical experience enhances science learning. *Psychological Science*, 26(6), 737–749.
- Kosso, P. (2002). The omniscient: beauty and scientific understanding. *International Studies in the Philosophy of Science*, 16(1), 39–48.
- Latour, B. (1986). Visualization and cognition: thinking with eyes and hands. In H. Kuklick (Ed.), *Knowledge and society: studies in the sociology of culture past and present* (Vol. 6, pp. 1–40). Greenwich: JAI Press.
- Lave, J., & Wenger, E. (1991). *Situated learning: legitimate peripheral participation* (Vol. 95). Cambridge: Cambridge University Press.
- Lewis, D. (1990). *Philosophical papers*. New York: Oxford University Press.
- Lewis, D. (2003). What experience teaches. In P. Ludlow, Y. Nagasawa, & D. Stoljar (Eds.), *There's something about Mary: essays on phenomenal consciousness* (pp. 77–103). Cambridge: MIT Press.
- Lipton, P. (2009). Understanding without explanation. In H. W. de Regt, S. Leonelli, & K. Eigner (Eds.), *Scientific understanding: philosophical perspectives* (pp. 43–63). Pittsburgh: Pittsburgh University Press.
- Loar, B. (1990). Phenomenal states. *Philosophical Perspectives*, 4, 81–108.
- Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology-Paris*, 102(1–3), 59–70.
- Markie, P. J. (2019). The value of knowing how. *Philosophical Studies*, 176(5), 1291–1304.
- Martin, A. (2016). GRAPES—Grounding representations in action, perception, and emotion systems: how object properties and categories are represented in the human brain. *Psychonomic Bulletin & Review*, 23(4), 979–990.
- Martone, M., Butters, N., Payne, M., Becker, J. T., & Sax, D. S. (1984). Dissociations between skill learning and verbal recognition in amnesia and dementia. *Archives of Neurology*, 41(9), 965–970.
- Merleau-Ponty, M. (2005). *Phenomenology of perception*. (C. Smith, Trans.). London: Routledge.
- Millar, R. (2010). Practical work. In J. Osborne & J. Dillon (Eds.), *Good practice in science teaching: what research has to say* (2nd ed., pp. 108–134). Open University Press.
- Minogue, J., & Jones, M. G. (2006). Haptics in education: exploring an untapped sensory modality. *Review of Educational Research*, 76(3), 317–348.
- Moser, P. K. (1987). Propositional knowledge. *Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition*, 52(1), 91–114.
- Nagel, T. (1974). What is it like to be a bat? *The Philosophical Review*, 83(4), 435–450.
- Nemirow, L. E. (1980). Review of Thomas Nagel, mortal questions. *Philosophical Review*, 89(3), 473–477.
- Nemirow, L. E. (1990). Physicalism and the cognitive role of acquaintance. In W. Lycan (Ed.), *Mind and cognition* (pp. 490–499). Cambridge: Cambridge University Press.
- Nola, R., & Irzik, G. (2005). *Philosophy, science, education and culture*. Dordrecht: Springer.
- Nott, M., & Wellington, J. (1996). When the black box springs open: practical work in schools and the nature of science. *International Journal of Science Education*, 18(7), 807–818.
- OCR. (2018). *GCSE (9–1) specification*. OCR: Gateway Science Physics A. Cambridge.
- Osborne, J., & Dillon, J. (2008). *Science education in Europe: critical reflections*. London: The Nuffield Foundation.
- Polanyi, M. (1966). *The tacit dimension*. Chicago: University of Chicago Press.
- Polanyi, M. (1974). *Personal knowledge*. Chicago: University of Chicago Press.
- Pouw, W. T. J. L., van Gog, T., Zwaan, R. A., & Paas, F. (2016). Augmenting instructional animations with a body analogy to help children learn about physical systems. *Frontiers in Psychology*, 7(860), 1–11.
- Reichenbach, H. (1938). *Experience and prediction. An analysis of the foundations and the structure of knowledge*. Chicago: University of Chicago Press.
- Reiner, M. (1998). Thought experiments and collaborative learning in physics. *International Journal of Science Education*, 20(9), 1043–1058.
- Reiner, M. (1999). Conceptual construction of fields through tactile interface. *Interactive Learning Environments*, 7(1), 31–55.

- Ryle, G. (1945). Knowing how and knowing that. In *Proceedings of the Aristotelian Society* (Vol. 46, pp. 1–16).
- Sartwell, C. (1991). Knowledge is merely true belief. *American Philosophical Quarterly*, 28(2), 157–165.
- Schier, E. (2008). The knowledge argument and the inadequacy of scientific knowledge. *Journal of Consciousness Studies*, 15(1), 39–62.
- Shapiro, L., & Stolz, S. A. (2019). Embodied cognition and its significance for education. *Theory and Research in Education*, 17(1), 19–39.
- Sheets-Johnstone, M. (2011). *The primacy of movement*. Amsterdam: John Benjamins Publishing Company.
- Sinatra, G. M., Southerland, S. A., McConaughy, F., & Demastes, J. W. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. *Journal of Research in Science Teaching*, 40(5), 510–528.
- Smith, M. U., & Siegel, H. (2004). Knowing, believing, and understanding: what goals for science education? *Science & Education*, 13(6), 553–582.
- Smith, M. U., & Siegel, H. (2016). On the relationship between belief and acceptance of evolution as goals of evolution education: twelve years later. *Science & Education*, 25(5–6), 473–496.
- Squire, L. R. (1986). Mechanisms of memory. *Science*, 232(4758), 1612–1619.
- Stanley, J., & Williamson, T. (2001). Knowing how. *The Journal of Philosophy*, 98(8), 411–444.
- Starmans, C., & Friedman, O. (2012). The folk conception of knowledge. *Cognition*, 124(3), 272–283.
- Stoljar, D. (2005). Physicalism and phenomenal concepts. *Mind and Language*, 20(5), 469–494.
- Sullivan, J. V. (2018). Learning and embodied cognition: a review and proposal. *Psychology Learning & Teaching*, 17(2), 128–143.
- Swaak, J., & de Jong, T. (1996). Measuring intuitive knowledge in science: the development of the What-If Test. *Studies in Educational Evaluation*, 22(4), 341–362.
- Taber, K. S. (2014). The significance of implicit knowledge for learning and teaching chemistry. *Chemistry Education Research and Practice*, 15(4), 447–461.
- Toulmin, S. (1961). *Foresight and understanding*. New York: Harper & Row.
- Turri, J. (2012). Is knowledge justified true belief? *Synthese*, 184(3), 247–259.
- Tye, M. (1986). The subjective qualities of experience. *Mind*, 95(377), 1–17.
- Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2012). The malleability of spatial skills: a meta-analysis of training studies. *Psychological Bulletin*, 139(2), 352–402.
- Van Der Steen, W. J., & Sloep, P. B. (1993). Philosophy, education, and the explosion of knowledge. *Interchange*, 24(1–2), 19–28.
- Van Gluick, R. (2004). So many ways of saying no to Mary. In P. Ludlow, Y. Nagasawa, & D. Stoljar (Eds.), *There's something about Mary: essays on phenomenal consciousness* (pp. 365–405). Cambridge: MIT Press.
- Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817–835.
- Wallis, C. (2008). Consciousness, context, and know-how. *Synthese*, 160(1), 123–153.
- Weisberg, S. M., & Newcombe, N. S. (2017). Embodied cognition and STEM learning: overview of a topical collection in CR:PI. *Cognitive Research: Principles and Implications*, 2(1), 38.
- Wellington, J., & Ireson, G. (2012). *Science learning, science teaching* (3rd ed.). Abingdon: Routledge.
- Wellington, J., & Osborne, J. F. (2001). *Language and literacy in science education*. Buckingham: Open University Press.
- Willingham, D. T. (2009). *Why don't students like school: a cognitive scientist answers questions about how the mind works and what it means for the classroom*. San Francisco: Jossey-Bass.
- Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4), 625–636.
- Winch, C. (2013). Curriculum design and epistemic ascent. *Journal of Philosophy of Education*, 47(1), 128–146.
- Yandell, J. (2017). Culture, knowledge and power: what the conservatives have learnt from E.D. Hirsch. *Changing English*, 24(3), 246–252.
- Young, M. (2008). *Bringing knowledge back in: from social constructivism to social realism in the sociology of education*. London: Routledge.
- Zagzebski, L. (2001). Recovering understanding. In M. Steup (Ed.), *Knowledge, truth, and duty: essays on epistemic justification, responsibility and virtue* (pp. 235–251). Oxford: Oxford University Press.